Impact of PVDIS with 22 GeV electrons at JLab on the nucleon strangeness

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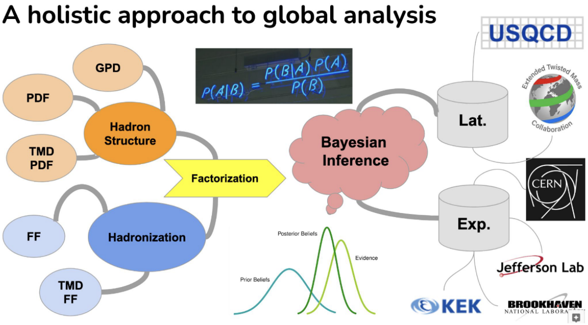
JAM Collaboration

The Jefferson Lab Angular Momentum (JAM) Collaboration is an enterprise involving theorists, experimentalists, and computer scientists from the Jefferson Lab community using QCD to study the internal quark and gluon structure of hadrons and nuclei. Experimental data from high-energy scattering processes are analyzed using modern Monte Carlo techniques and state-of-the-art uncertainty quantification to simultaneously extract various quantum correlation functions, such as parton distribution functions (PDFs), fragmentation functions (FFs), transverse momemtum dependent (TMD) distributions, and generalized parton distributions (GPDs). Inclusion of lattice QCD data and machine learning algorithms are being explored to potentially expand the reach and efficacy of JAM analyses and our understanding of hadron structure in QCD.

TL;DR: Group interested in understanding partonic structure of nucleons/hadrons through determination of relevant QCFs via global QCD analysis

JAM Global Analysis Paradigm

Factorization: $\mathcal{O} = \mathcal{H} \otimes \text{QCFs}$

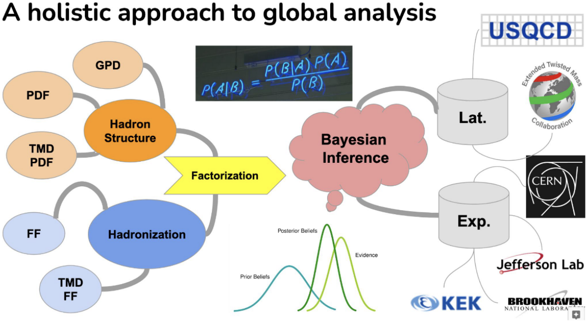


$$f(x) = \mathcal{N} x^{\alpha} (1-x)^{\beta} (1 + \gamma\sqrt{x} + \delta x)$$

JAM Global Analysis Paradigm

Factorization: $\mathcal{O} = \mathcal{H} \otimes \text{QCFs}$

Bayes' theorem:
$\rightarrow \mathcal{P}(\mathbf{a}|\text{data}) \sim \mathcal{L}(\mathbf{a}, \text{data})\pi(\mathbf{a})$
$\rightarrow \mathcal{L}(\mathbf{a}, \text{data}) = \exp(-\chi^2(\mathbf{a}, \text{data})/2)$



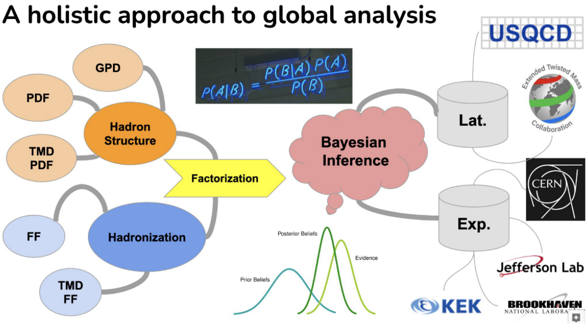
$$\chi^2(\mathbf{a}, \text{data}) = \sum_{e,i} \left(\frac{d_{e,i} - \sum_k r_{e,k} \beta^k_{e,i} - T_{e,i}(\mathbf{a})/N_e}{\alpha_{e,i}} \right)^2 + \sum_{e,k} r^2_{e,k} + \sum_e \left(\frac{1 - N_e}{\delta N_e} \right)^2$$

JAM Global Analysis Paradigm

Factorization: $\mathcal{O} = \mathcal{H} \otimes \text{QCFs}$

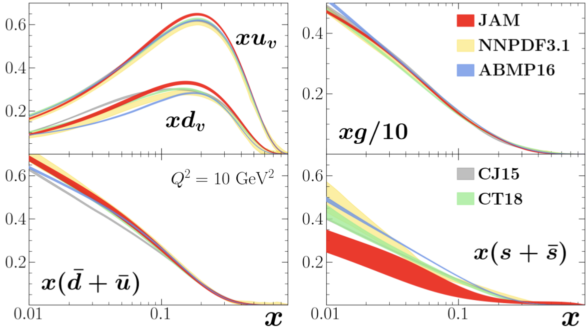
Bayes' theorem:
$\rightarrow \mathcal{P}(\mathbf{a}|\text{data}) \sim \mathcal{L}(\mathbf{a}, \text{data})\pi(\mathbf{a})$
$\rightarrow \mathcal{L}(\mathbf{a}, \text{data}) = \exp(-\chi^2(\mathbf{a}, \text{data})/2)$

Monte Carlo Replicas: $\tilde{\boldsymbol{d}} \sim \mathcal{N}(\boldsymbol{d}, \Sigma)$



$$\mathrm{E}[\mathcal{O}] = \frac{1}{N_{\text{reps}}} \sum_{i=1}^{N_{\text{reps}}} \mathcal{O}(\boldsymbol{a}_i) \quad \mathrm{V}[\mathcal{O}] = \frac{1}{N_{\text{reps}}} \sum_{i=1}^{N_{\text{reps}}} \Big(\mathcal{O}(\boldsymbol{a}_i) - \mathrm{E}[\mathcal{O}]\Big)^2$$

Current Status – PDFs



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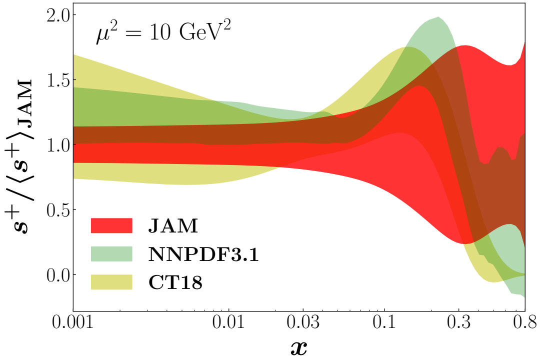
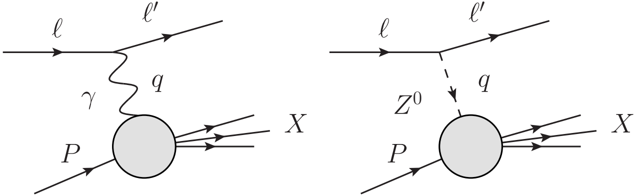


Parity-Violating Deep-Inelastic Scattering (PVDIS)



$$Q^2 = -q^2 = -(\ell - \ell')^2$$

$$x_{\mathrm{B}} = \frac{Q^2}{2P\cdot q} \qquad s = (P+\ell)^2$$

$$y = \frac{P\cdot q}{P\cdot \ell} \qquad W^2 = (P+q)^2$$

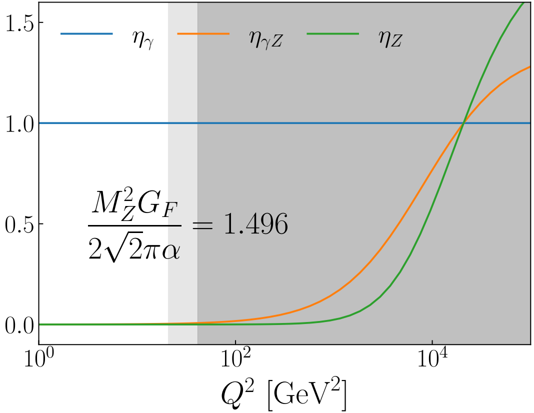
$$\frac{\mathrm{d}\sigma}{\mathrm{d}E'\,\mathrm{d}\Omega} = \frac{1}{2(s-M^2)}\frac{E'}{2(2\pi)^3}\sum_X \int \mathrm{d}\Phi_X (2\pi)^4 \delta^{(4)}(P+q-P_X)\,\underbrace{|\mathcal{M}_\gamma + \mathcal{M}_Z|^2}_{|M_\gamma|^2 + 2\,\mathrm{Re}(M_\gamma M_Z^*) + |M_Z|^2}$$

PVDIS cross section

$$\frac{d\sigma_{\lambda_\ell}}{dx_B\,dy} = \frac{2\pi\alpha^2 y}{Q^4}\sum_i \eta_i C_i L^{\gamma}_{\mu\nu} W^{\mu\nu}_{i,U}$$

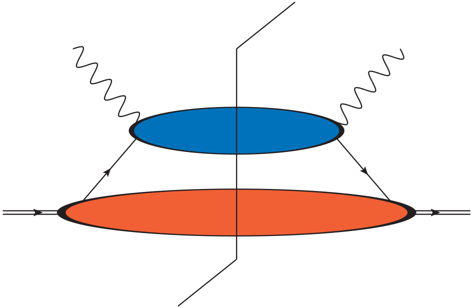
$$W^{\mu\nu}_{i,U} = \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right)F^i_1(x_B, Q^2)$$
$$+\left(P^\mu - \frac{P\cdot q}{q^2}q^\mu\right)\left(P^\nu - \frac{P\cdot q}{q^2}q^\nu\right)\frac{F^i_2(x_B,Q^2)}{P\cdot q}$$
$$+ i\epsilon^{\mu\nu\alpha\beta}\frac{P_\alpha q_\beta}{2P\cdot q}F^i_3(x_B,Q^2)$$

$$\eta_{\gamma Z} = \frac{M_Z^2 G_F}{2\sqrt{2}\pi\alpha}\frac{Q^2}{Q^2+M_Z^2}, \quad \eta_Z = \eta_{\gamma Z}^2$$



Collinear factorization and the parton model

$$W_{i,U}^{\mu\nu} = \sum_i \int_{\xi_{\min}}^{1} \frac{\mathrm{d}\xi}{\xi} \widehat{W}_{i,U}^{\mu\nu}(\hat{x}, Q^2) f_{i/P}(\xi, \mu^2)$$



At LO in α_S :

$$\rightarrow F_1^{\{\gamma,\gamma Z,Z\}}(x_{\mathrm{B}}, Q^2) = \frac{1}{2} \sum_q \left\{ e_q^2,\ 2e_q g_V^q,\ (g_V^q)^2 + (g_A^q)^2 \right\} \underbrace{\left[q(x_{\mathrm{B}}, Q^2) + \overline{q}(x_{\mathrm{B}}, Q^2) \right]}_{q^+(x_{\mathrm{B}},Q^2)}$$

$$\rightarrow F_3^{\{\gamma,\gamma Z,Z\}}(x_{\mathrm{B}}, Q^2) = \sum_q \left\{ 0,\ 2e_q g_A^q,\ 2g_V^q g_A^q \right\} \underbrace{\left[q(x_{\mathrm{B}}, Q^2) - \overline{q}(x_{\mathrm{B}}, Q^2) \right]}_{q^-(x_{\mathrm{B}},Q^2)}$$

Parity-Violating Asymmetry

$$A_{\mathrm{PV}} = \frac{\mathrm{d}\sigma_+ - \mathrm{d}\sigma_-}{\mathrm{d}\sigma_+ + \mathrm{d}\sigma_-} \approx \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[2g_A^e \frac{F_1^{\gamma Z}}{F_1^\gamma} Y_1 + g_V^e \frac{F_3^{\gamma Z}}{F_1^\gamma} Y_3\right]$$

$$Y_1 = \left(\frac{1+R^{\gamma Z}}{1+R^\gamma}\right)\frac{1+(1-y)^2 - \frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma Z}}\right]}{1+(1-y)^2 - \frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma}}\right]}, \quad r^2 = 1 + 4M^2 x_{\mathrm{B}}^2/Q^2$$

$$Y_3 = \left(\frac{1+R^{\gamma Z}}{1+R^\gamma}\right)\frac{1-(1-y)^2}{1+(1-y)^2 - \frac{y^2}{2}\left[1+r^2-\frac{2r^2}{1+R^{\gamma}}\right]}, \quad R^i = \frac{F_2^i}{2x_{\mathrm{B}}F_1^i} r^2 - 1$$

Parity-Violating Asymmetry

$$A_{\mathrm{PV}} = \frac{\mathrm{d}\sigma_+ - \mathrm{d}\sigma_-}{\mathrm{d}\sigma_+ + \mathrm{d}\sigma_-} \approx \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[2g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} Y_1 + g_V^e \frac{F_3^{\gamma Z}}{F_1^{\gamma}} Y_3\right]$$

$$Y_1 = \left(\frac{1 + R^{\gamma Z}}{1 + R^{\gamma}}\right) \frac{1 + (1-y)^2 - \frac{y^2}{2}\left[1 + r^2 - \frac{2r^2}{1+R^{\gamma Z}}\right]}{1 + (1-y)^2 - \frac{y^2}{2}\left[1 + r^2 - \frac{2r^2}{1+R^{\gamma}}\right]}, \quad r^2 = 1 + \cancel{4M^2 x_{\mathrm{B}}^2/Q^2}$$

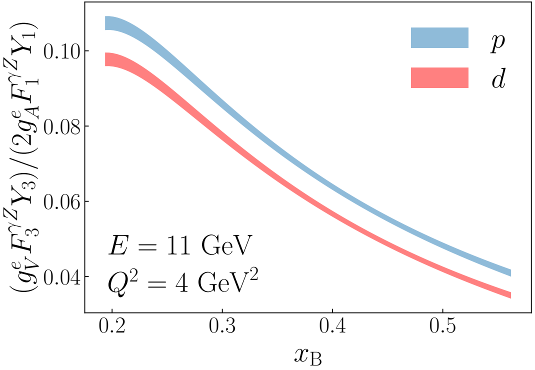
$$Y_3 = \left(\frac{1 + R^{\gamma Z}}{1 + R^{\gamma}}\right) \frac{1 - (1-y)^2}{1 + (1-y)^2 - \frac{y^2}{2}\left[1 + r^2 - \frac{2r^2}{1+R^{\gamma}}\right]}, \quad R^i = \frac{F_2^i}{2x_{\mathrm{B}} F_1^i} r^2 - 1 = 0$$

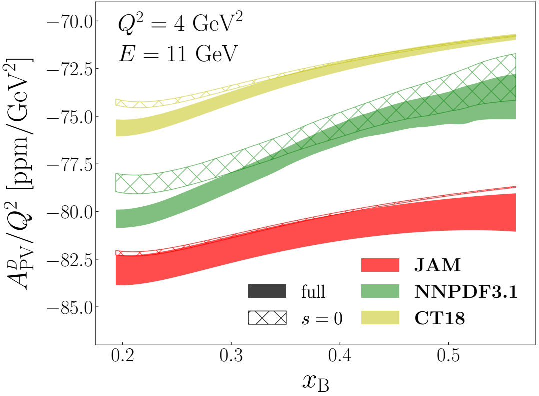
Parity-Violating Asymmetry

$$A_{\mathrm{PV}} = \frac{\mathrm{d}\sigma_+ - \mathrm{d}\sigma_-}{\mathrm{d}\sigma_+ + \mathrm{d}\sigma_-} \approx \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[2g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} Y_1 + g_V^e \frac{F_3^{\gamma Z}}{F_1^{\gamma}} Y_3\right]$$

$$Y_1 = 1, \quad Y_3 = \frac{1-(1-y)^2}{1+(1-y)^2}$$

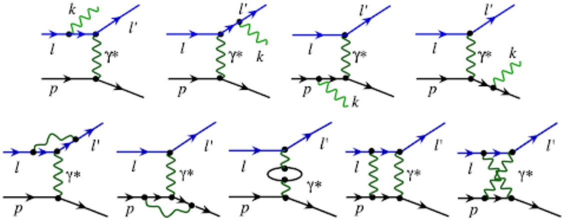
A_{PV} on a deuterium target



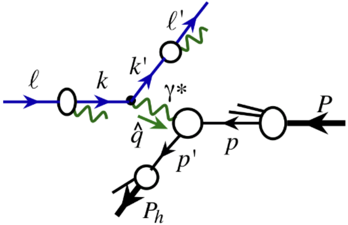


$$A_{\mathrm{PV}}^D \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[\left(\frac{9}{5} - 4\sin^2\theta_{\mathrm{W}}\right) + \frac{2}{25}\frac{s^+}{u^+ + d^+}\right]$$

Hybrid QED+QCD factorization



QED
resummation



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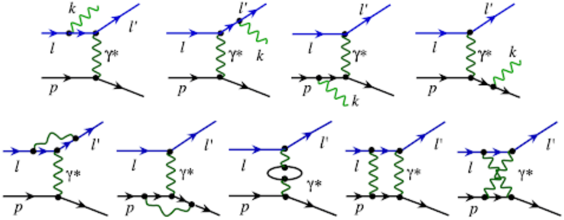
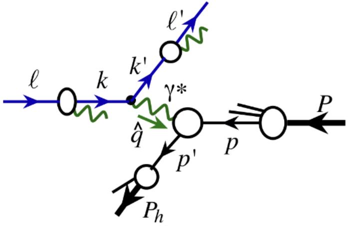
$$\frac{\mathrm{d}\sigma_{(U/L)U}}{\mathrm{d}x_\mathrm{B}\,\mathrm{d}y} = \int_{\zeta_\mathrm{min}}^{1} \frac{\mathrm{d}\zeta}{\zeta^2} \underbrace{D_{e/e}(\zeta,\mu^2)}_{\text{LFF}} \int_{\xi_\mathrm{min}}^{1} \mathrm{d}\xi \underbrace{f_{e/e}(\xi,\mu^2)}_{\text{LDF}} \left[\frac{Q^2}{x_\mathrm{B}}\frac{\hat{x}_\mathrm{B}}{\hat{Q}^2}\right] \frac{\mathrm{d}\hat{\sigma}_{(U/L)U}}{\mathrm{d}\hat{x}_\mathrm{B}\,\mathrm{d}\hat{y}}$$

Hybrid QED+QCD factorization



QED
resummation



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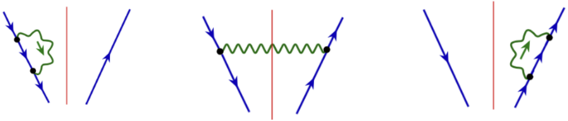
$$f_{i/e}(\xi) = \int \frac{\mathrm{d}z^-}{4\pi} e^{i\xi\ell^+ z^-} \langle e|\overline{\psi}_i(0)\gamma^+\Phi_{[0,z^-]}\psi_i(z^-)|e\rangle$$

$$D_{e/j}(\zeta) = \frac{\zeta}{2}\sum_X \int \frac{\mathrm{d}z^-}{4\pi} e^{i\ell^+ z^-/\zeta}\mathrm{Tr}\Big[\gamma^+ \langle 0|\overline{\psi}_j(0)\Phi_{[0,\infty]}|e,X\rangle\ \langle e,X|\psi_j(z^-)\Phi_{[z^-,\infty]}|0\rangle\Big]$$

LDF and LFF RGE



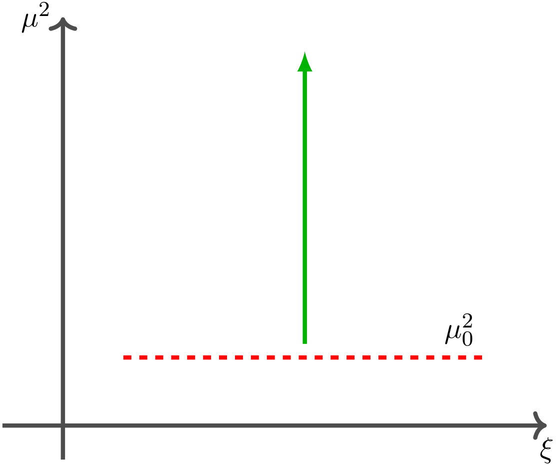
$$\frac{\partial f_{i/\ell}(\xi,\mu^2)}{\partial \ln\mu^2} = \sum_j \int_\xi^1 \frac{\mathrm{d}z}{z} P_{ij}(z) f_{j/\ell}\left(\frac{z}{\xi},\mu^2\right)$$

$$f^{(0)}_{e/e}(\xi,\mu_0^2) = \delta(\xi-1)$$

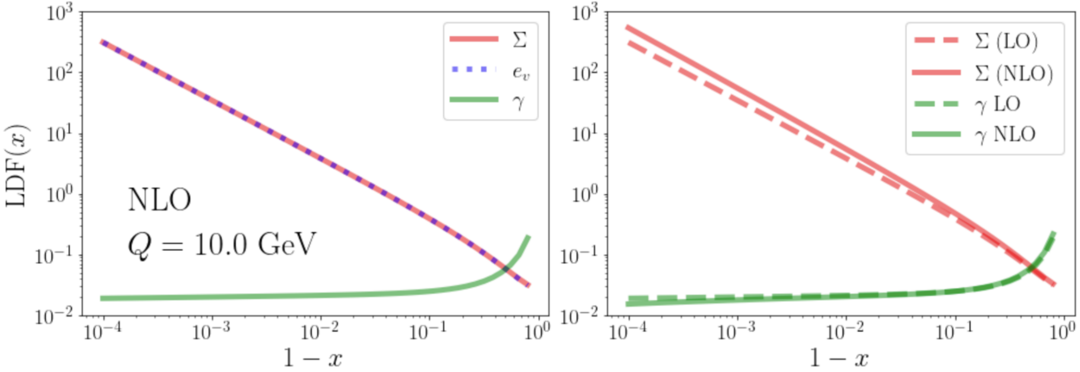
$$f^{(1)}_{e/e}(\xi,\mu_0^2) = \frac{\alpha}{2\pi}\left[\frac{1+\xi^2}{1-\xi}\ln\frac{\mu_0^2}{(1-\xi)^2 m_e^2}\right]_+$$

$$D^{(0)}_{e/e}(\zeta,\mu_0^2) = \delta(\zeta-1)$$

$$D^{(1)}_{e/e}(\zeta,\mu_0^2) = \frac{\alpha}{2\pi}\left[\frac{1+\zeta^2}{1-\zeta}\ln\frac{\mu_0^2}{(1-\zeta)^2 m_e^2}\right]_+$$



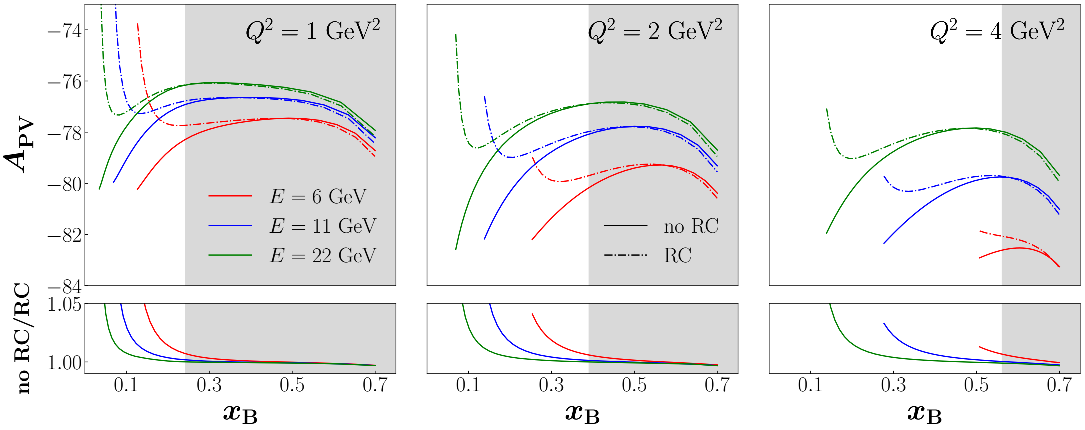
LDFs and LFFs



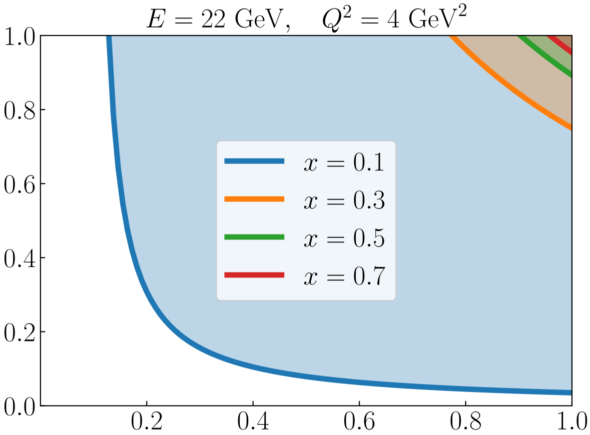
Subtraction "trick":

$$\to \int_{\xi_{\rm min}}^{1} \mathrm{d}\xi\, \mathcal{H}(\xi) f(\xi) = \int_{\xi_{\rm min}}^{1} \mathrm{d}\xi\, [\mathcal{H}(\xi) - \mathcal{H}(1)] f(\xi) + \mathcal{H}(1) \frac{\xi_{\rm min}}{2\pi i} \int \mathrm{d}N\, \xi_{\rm min}^{-N} \frac{F_N}{N-1}$$

Size of the radiative corrections



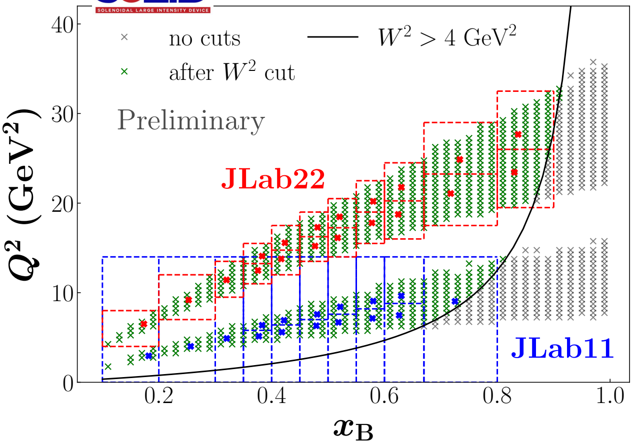
Why not fit all QCFs within hybrid factorization?



$$\mathrm{d}\sigma \sim \mathrm{LFF} \otimes \mathrm{LDF} \otimes \mathrm{PDF} \otimes \mathrm{d}\hat{\sigma}$$

→ additional convolution integrals
→ large radiative phase spaces
→ end point instabilities
→ how to model LFF, LDFs?

Simulating pseudo-data



$$\langle A_{PV} \rangle_{bin} = \sum_{i \in replicas} A_{PV,i} / N_{replicas}$$

Error budget:

$\rightarrow \delta^{stat} A_{PV} = \left(P \sqrt{\mathcal{L} \sigma_{bin}} \right)^{-1}$

$\rightarrow \delta^{syst} A_{PV} / A_{PV} = 0.5\%$

$\rightarrow \delta^{thy} A_{PV} = \left| A_{PV}^{(RC)} - A_{PV} \right|$

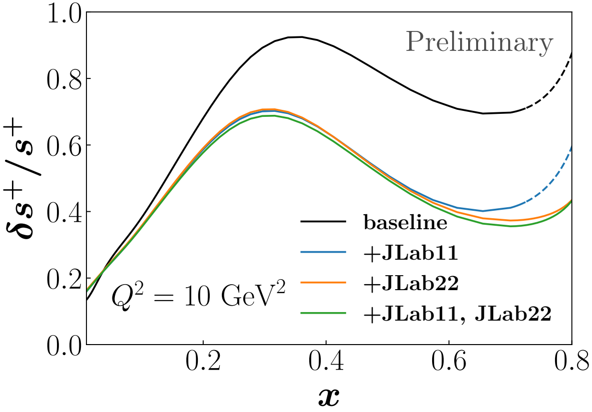
Note:

$\rightarrow P = 85\%$

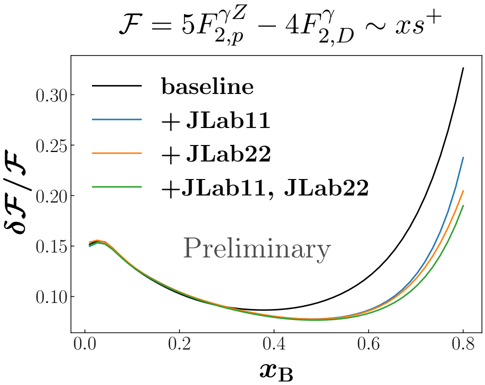
$\rightarrow \mathrm{d}\mathcal{L}/\mathrm{d}t = 4.85 \times 10^{38}$ cm^{-2} s^{-1}

$\rightarrow$ run time: 50 days/target

Impact on s^+



Preliminary
$\delta s^+/s^+$
x
$Q^2 = 10$ GeV^2
baseline
+JLab11
+JLab22
+JLab11, JLab22
0.0
0.2
0.4
0.6
0.8
1.0



$\mathcal{F} = 5F_{2,p}^{\gamma Z} - 4F_{2,D}^{\gamma} \sim xs^+$
$\delta\mathcal{F}/\mathcal{F}$
x_B
baseline
+JLab11
+JLab22
+JLab11, JLab22
Preliminary
0.10
0.15
0.20
0.25
0.30
0.0
0.2
0.4
0.6
0.8

Summary and Outlook

- Strange sea inside the nucleon needs to be constrained to achieve a better understanding of the longitudinal structure of the nucleon

→ also a primary source of uncertainty that contaminates BSM physics searches through A_{PV} measurements

- A_{PV} is a unique and clean observable that can be used in future global analyses to make progress toward this goal

- Future work:

→ Quantification of higher twist effects/uncertainties

→ electron/positron PVDIS for constraint of sea quark asymmetries

→ Charge symmetry violation

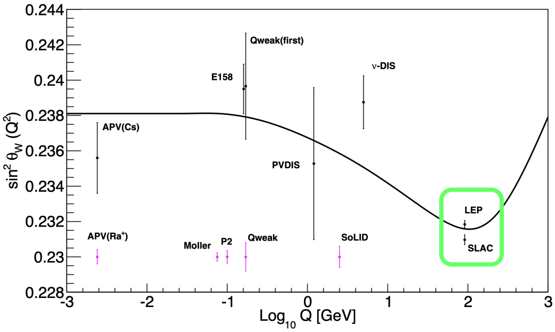
→ Polarized A_{PV}?

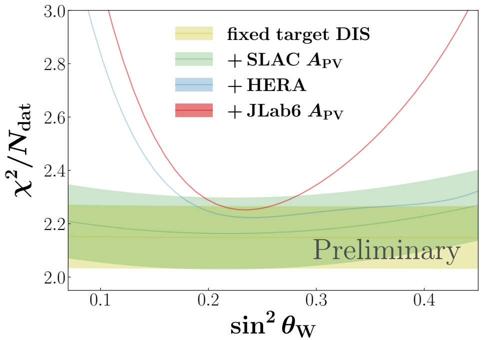
Backup Slides

Current Status – $\sin^2\theta_W$

Fundamental Standard Model parameter

$$\begin{pmatrix}\gamma \\ Z^0\end{pmatrix} = \begin{pmatrix}\cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W\end{pmatrix}\begin{pmatrix}B^0 \\ W^0\end{pmatrix}, \quad \cos\theta_W = \frac{m_W}{m_Z}$$





Current Status – $\sin^2\theta_W$

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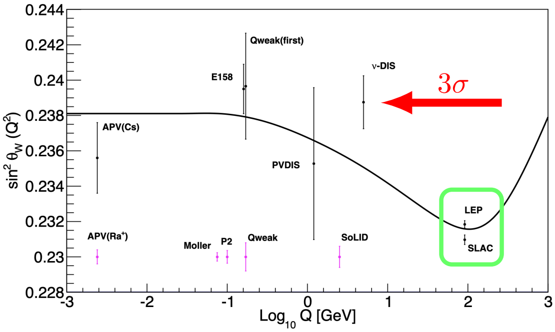

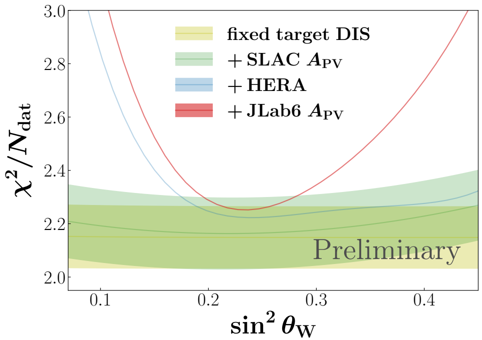

Combined impact on $\sin^2\theta_W$ and s^+